Eleventh International Congress on Sound and Vibration
July 5-8, 2004 • St. Petersburg, Russia

SPACE SHUTTLE CRAWLER TRANSPORTER SOUND ATTENUATION STUDY

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Abstract

The crawler transporter (CT) is the world's largest tracked vehicle known, weighing 6 million pounds with a length of 131 feet and a width of 113 feet. The Kennedy Space Center (KSC) has two CTs that were designed and built for the Apollo program in the 1960's, maintained and retrofitted for use in the Space Shuttle program. As a key element of the Space Shuttle ground systems, the crawler transports the entire 12-million-pound stack comprising the orbiter, the mobile launch platform (MLP), the external tank (ET), and the solid rocket boosters (SRB) from the Vehicle Assembly Building (VAB) to the launch pad. This rollout, constituting a 3.5–5.0-mile journey at a top speed of 0.9 miles-per-hour, requires over 8 hours to reach either Launch Complex 39A or B. This activity is only a prelude to the spectacle of sound and fury of the Space Shuttle launch to orbit in less than 10 minutes and traveling at orbital velocities of Mach 24.

This paper summarizes preliminary results from the Crawler Transporter Sound Attenuation Study, encompassing test and engineering analysis of significant sound sources to measure and record full frequency spectrum and intensity of the various noise sources and to analyze the conditions of vibration. Additionally, data such as ventilation criteria, plus operational procedures were considered to provide a comprehensive noise suppression design for implementation. To date, sound attenuation study and results on Crawler 2 have shown significant noise reductions ranging from 5 to 24 dBA.

INTRODUCTION

Technological advances and spin-offs attributable to the United Space (US) space program have transformed the way we live, work, and communicate around the world. However, one piece of the equipment that has virtually remained unchanged (lot of subsystem upgrades, but no major structural or vibraoacoustics modifications) over the last four decades is the CT. Designed for 100 miles of service, each CT has amassed over 1700+ miles hauling Saturn V's, Saturn 1B's, and the Space Shuttle, while being the quintessential workhorse of the US space program. The "mighty tortoise" has been featured on Discovery channel [1]. In 1977, ASME named the Crawler Transporters, as the 18th National Historic Mechanical Engineering Landmarks [2]. In celebration of the fortieth anniversary of world's largest tracked land vehicles, this paper briefly outlines on-going sound attenuation study, planned modifications that are envisioned, and those partially implemented. The goal is to enhance the reliability, availability, and maintainability of the CT for return to flight of the Space Shuttle launch operations.

SOUND ATTENUATION METHODOLOGY

The approach involved sound pressure level and sound intensity level measurements of the significant noise sources on the Crawler Transporter. Sound intensity measurements were used to assist in determining the significance of noise sources located in multi-source noise environment. A preliminary assessment of CT noise sources and as-built issues such as the engine and generator sets exhausting to the underside of CT's superstructure; the engines radiators drawing cooling air inwards towards the CT housing; the Jacking Equalization and Leveling System (JEL) system pumps, steering hydraulic system and super charger pumps that are rigidly mounted to the CT superstructure with their hydraulic lines crisscrossing under the CT and inducing noise into all areas of the CT, including the Control Room and the Cabs; the ventilation cooling air exiting through louvered openings in the floor of the Crawler Transporter Engine and Equipment House; and lastly, the noise sources surrounding the movement of the trucks particularly the jacking and leveling system, the steering system, the truck propulsion motors, mechanical noise associated with the movement of the shoes over the bogies and sound of the crawler way gravel being crushed. Sound pressure level measurements were made (Table 1) of the existing noise sources that could be readily identified and isolated from other sources. Many of these sound pressure level measurements were completed in year 2000, with the Crawler Transporter connected to shore power to assist in the isolation process.

Based on the initial survey, a total of nine (9) separate noise mitigation recommendations were targeted for an overall reduction in the Control Room noise level to 85 dBA or below, lowering the overall Engine/Pump room noise level by 5 dBA or better and reducing the overall noise level in the general area under and around the CT by 8 to 10 dBA. Initial recommendations included an Acoustical isolation wall between the Control Room and the Engine/Pump Room, as well as installing acoustical vestibules and doors at the four Engine/Pump Room's door openings, installing absorption panels on the Engine/Pump Room's ceiling and walls, isolating the JEL skid and piping from the CT's superstructure, providing in-line hydraulic silencers for the JEL systems, installing inlet acoustical fan forced ventilation hoods under the CT's floor on the existing louvered floor openings, replacing wall inlet vent fans with acoustical fan forced exhaust ventilation hoods, and lastly replacing and isolating the engine muffler and exhaust systems from the CT's superstructure.

Instrumentation

Sound level measurements of Crawler Transporter #2 were undertaken during the site visits on May 12 - 13 and August 12 - 14, 2000. Sound pressure level measurements were undertaken on the first visit with the CT stationary and sound intensity and sound pressure level measurements were undertaken on the second visit during a shuttle roll-out. The sound pressure level measurements were conducted with a Brüel & Kjær Model 2260 Precision Real Time Sound Analyzer and a Brüel & Kjær Model 4189 Microphone. These systems measure and record 1/3-octave band frequency sound pressure level spectra. The measurement system was field calibrated at the start of each series of measurements and checked upon completion using a Brüel & Kjær Model 4231 Sound Pressure Level Calibrator. The sound intensity level measurements were conducted with two Brüel & Kjær Model 2260 Precision Real Time Sound Analyzers, each equipped with a Brüel & Kjær Model 4197 Microphone Pair mounted on a 2683 Sound Intensity Probe. These systems were used to measure and record 1/3 octave band frequency sound intensity and sound level spectra. The measurement systems were field calibrated at the start of each series of measurements and checked upon completion using a Brüel & Kjær Model 3541 Sound Intensity Calibrator and Model 4228 Piston Phone.

Measurements

Sound Pressure Level (SPL) measurements were taken of the ventilation fans and radiator fans and Sound Intensity measurements were taken throughout the inside and around the CT periphery including the ALCO/WHITE engines, Hydraulic Supercharger Pumps, Steering Pumps, JEL Pumps, Control Room Floor and Walls, Cab 1 Side/Rear Walls, Truck front/outside faces, and JEL cylinder corners. Sound Intensity Contours (dBA), Sound Intensity and Pressure Level Bar Graphs, and Sound Pressure Level Bar Graphs are well documented for most the CT areas [3].

Processed Data – Sound Pressure Level (SPL)

The sound pressure level measurements provide an overall sound level of all the combined noise sources at the microphone position. Thus, sound pressure levels are very useful when it is possible to measure one piece of equipment at a time. When undertaking interior sound level measurements the sound pressure level includes the direct sound radiating off of a sound emitting surface, reflected sound from first and second reflections off of various surfaces, and the reverberant component from sound that has reflected many times from the various interior surfaces present.

Thus, sound pressure level measurements are not as useful for discerning the amount of sound caused by an individual sound source in a multi-source environment. Sound pressure level measurements were undertaken of the various electrical powered ventilation fans and radiator fans without other equipment operating. Their sound level does not change with the load on the Crawler Transporter only their duration of operation changes with load. The measured 1/3 octave band sound levels are presented as bar graphs in the Reduced Data in the CT Sound Attenuation Study and Installation document [3].

Processed Data – Sound Intensity Level (SIL)

Sound intensity level measurements were undertaken of the major noise sources that change intensity level with load including the diesel generator sets and the hydraulic systems as well as various control room and cab surfaces. The sound intensity level measurements consisted of a series of measurements taken on a known grid of the noise source or surface under consideration. A 0.5-meter measurement grid was used for all sound intensity level measurements with the exception of the trucks, in which case a 0.75-meter measurement grid was used. Sound pressure level measurements are automatically recorded along with the sound intensity measurements.

The sound intensity measurements provide an indication of both the sound intensity level and the direction of the sound energy flow. Thus, a sound intensity measurement indicates that sound may be flowing out of or into a surface. In order to visualize the sound energy flow, the sound intensity data was input into mapping software to generate 1/3 octave band sound intensity noise contours of the major noise sources and surfaces. The contours are presented as 2D maps with an outline of the equipment overlaid onto the contour and a 3D contour map to provide a graphic representation of sound energy flow from the surface of interest. The sound level is represented by different colors for both the 2D and 3D maps. The sound intensity contours are presented in the reduced data sound contours appendix and an example of the raw sound intensity data is presented in a tabular form in the CT Sound Attenuation Study and Installation document released in 2000 [3].

STUDY RESULTS AND ENHANCEMENTS

Phase 1

It consisted of removal of the old (Figure 1) and installing new upgraded engine exhaust mufflers (Figure 2) and upgrading engine/pump room ventilation. The first phase was designed to reduce noise levels around the CT both on the ground and on the walkways. A secondary benefit of the above upgrades resulted in improved air quality in the engine/pump room. Previously, the engine exhaust outlets were located directly under the CT, thus operators when walking under the CT to inspect the large trucks would be close to the exhaust outlets, and thus they were exposed to the noise and diesel smoke. Along with the upgraded mufflers the exhaust pipes have been extended out beyond the end of the CT to terminate up in the front of the radiator fans (Figure 3). This greatly increased the distance between the operator and the exhaust outlet noise and the diesel smoke. Utilizing the air movement from the radiator fans as the direction was reversed; the diesel smoke is now blown out from the end of the CT rather than in the past as it was exhausted under the CT, thus it would drift up into the CT.

In the past, the ventilation air was drafted in from the sidewalls (Figure 4) for the engine/pump room whereby it would first sweep across the engines before being driven down over the workers and then exhausted out through twelve louvered outlets in the floor. The ventilation air is now drawn in from under the CT through twelve filtered fan forced ventilation inlet hoods (Figure 5), thus using the coolest air available. The cool air is forced up through the floor grates, and first sweeps across the workers. It then flows across the engines on its way to the ceiling before being exhausted outside via fourteen silenced fan forced exhaust outlets (Figure 6). This change in airflow direction as well as the increased volume of ventilation air allows the engine/pump room to operate with a reasonable temperature increase, and allows the doors to remain closed during operations. The closed doors in conjunction with the silenced floor and wall ventilation openings have significantly reduced noise levels around the CT both on the catwalks and on the ground while enhancing operational conditions for the CT Crew.

Phase 2

This phase of the noise control will be noise suppression of the JEL hydraulic systems. The hydraulic systems are all hard mounted to the CT's superstructure and use the rigid pipe except for its final connections to the hydraulic cylinders. The pump tone generated by the JEL hydraulic systems was identified as one of the major noise sources in the control room and in the driver cabs even though the hydraulic lines do not run directly under these areas. The JEL system noise control measures include mounting the JEL motors and pump skids on rubber isolators, the use of elastomeric pipe mounting clamps to isolate the hydraulic lines from the CT's superstructure, installation of flexible hose between the pumps and the rigid hydraulic lines and installation of in-line hydraulic silencers to attenuate the pump tone. Currently, the schedule is to conduct this work in 2004.

Phase 3

This phase will encompass the installation of acoustical absorption on the walls and ceilings of the engine/pump room, use of sound lock vestibules at the engine/pump room's doors, and application of an upgraded sound reduction wall between the engine/pump room and the control room. This will reduce the noise levels in the control room, and further lower noise levels outside of the CT because of a decrease in the reverberant sound level inside the engine/pump room.

CONCLUSIONS

Following the completion of the Phase 1 of CT-2, the preliminary noise level readings indicate significant reductions as outlined in Table 2. On the catwalk on the side of the CT, the sound level dropped by 24 dBA when the ventilation air exhaust openings were addressed, which reduced that noise level down from 101 dBA to 77 dBA. Additionally, on the ends of CT the new ventilation air exhaust openings suppressed the exhaust opening noise level by 16 dBA (down from 101 dBA to 85 dBA).

The new ventilation systems allow the CT to operate with the engine/pump room doors closed, thus fostering a quieter environment on the catwalks, as well as under and around the CT. Now, with phase I complete on CT # 2, the difference in noise level on the catwalks with the doors open and closed is 11 dBA, down from 97 dBA with the doors open to 86 dBA with the doors closed.

Under the center of the CT with the engines and ventilation fans operating, the noise level was reduced by 9 dBA, down from 93 dBA to 84 dBA.

The CT's AC power is generated from two 1073 HP White engines. The AC engine exhaust outlet noise level was reduced from 85 dBA at 600 RPM down to 75 dBA, and from 91 dBA at 900 RPM down to 86 dBA. Due to recent modifications to the venturi exhaust tips, these sound levels should now be lower than the preliminary measurements.

The CT's DC power is generated from two 2750 HP Alco engines. The DC engine exhaust outlet noise level was reduced by 13 dBA when operating at 350 RPM, down from 80 dBA to 67 dBA, and down from 93 dBA to 84 dBA when operating at 1000 RPM.

The three implemented upgrades to-date, involving replacement and isolation of engine mufflers and exhausts, floor louver noise attenuation inlet fan hoods, and replacement of wall exhaust vent fans with acoustical hoods, aided in eliminating diesel smoke (more of a nuisance during operations) and reduction in operating temperature within the engine/pump room from ambient.

The results presented in this report are reflective of the Phase I noise abatement for the CT. This phase involved the Engine Exhaust Silencers and the CT Inlet and Exhaust Ventilation systems. Phase 2 will cover the Hydraulic Noise Abatement modifications. Phase 3 will include the installation of acoustical panels on the Engine/Pump Room's Wall and Ceiling, and installing an Acoustical Isolation Wall between the Control Room and the Engine/Pump Room.

ACKNOWLEDGEMENT

The article is dedicated to the entire CT design, operations and maintenance crew, for displaying unparallel pride in ownership of two Crawler Transporters and displaying pro-active stance to support myriad of requirements put forth by NASA management. The authors would like to thank NASA Ground Systems Management team headed by Rick Blackwelder and Perry Becker, for providing a platform to explore, develop, implement state-of-the-art techniques by thinking outside the box and

subsequent peer review at International forums. Thanks are due to Mike Wetmore, Shuttle Processing Director, for raising the bar towards the development and commercialization of cutting-edge technologies, while embellishing NASA's global technological leadership role.

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2. The American Society of Mechanical Engineers, "Crawler Transporters of Launch Complex 39, Kennedy Space Center," National Historic Landmark (1977).
3. Crawler Transporter Sound Attenuation Study and Installation, NSI documentation, Phase II Report (2000).
4. MacDonald, R. and Faszer, C., "Private Communication, CT Article – Noise Data," (2003)

Table 1. Noise reduction targets from the noise study

Description	Existing Noise Level (dBA)	Expected Noise Reduction (dBA)	Expected Noise Level (dBA)
Control Room	86 to 89	10 to 15	71 to 79
CABs	74 to 76	8 to 12	62 to 68
Ventilation Fans	86 to 89	10 to 15	71 to 79
White Superior Exhausts	91 to 92	10 to 15	76 to 82
Alco Exhausts	92 to 93	10 to 15	77 to 83

Table 2. Preliminary Noise reductions after installation of Phase I Noise Control

Description	**Measured Sound Levels (dBA)**		**Noise Reduction (dBA)**
	Before	**After**	
CT side ventilation air exhaust openings	101	77	24
CT end ventilation air exhaust openings	101	85	16
Existing 6 blade ventilation air intake openings	88	72	16
Existing 2 blade ventilation air intake openings	91	72	19
Under Centre of Crawler Engines & ventilation fans operating	93	84	9
On catwalk engine room door open and closed	97	86	11
White Engines 600 RPM exhaust outlet	85	75	10
White Engines 900 RPM exhaust outlet	91	86	5
Alco Engines 350 RPM exhaust outlet	80	67	13
Alco Engines 1000 RPM exhaust outlet	93	84	9

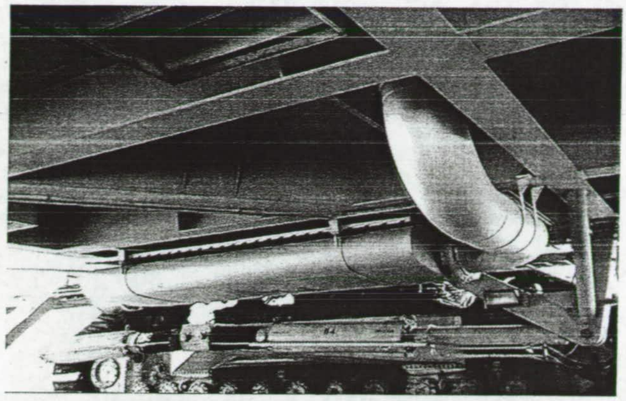

Figure 1. Old ALCO Engine Muffler and portion of old exhaust floor gratings

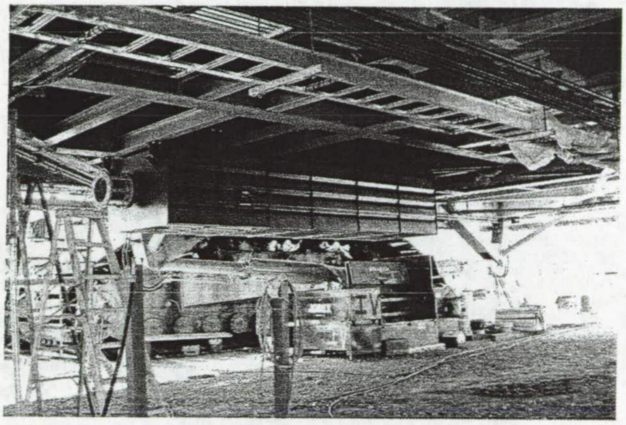

Figure 2. One of two New ALCO Engine Mufflers (White Engines have only 1 Muffler)

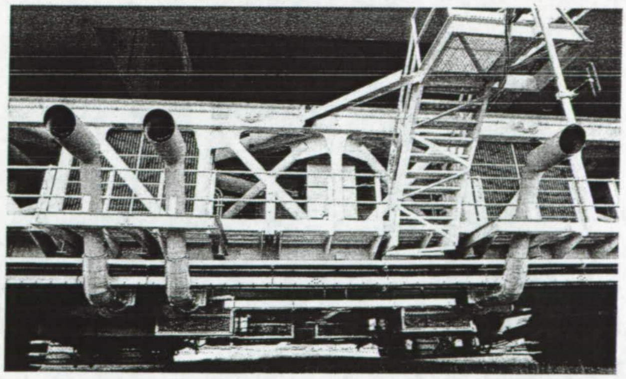

Figure 3. Extended Engine Exhaust Outlets terminating in front of radiator fans

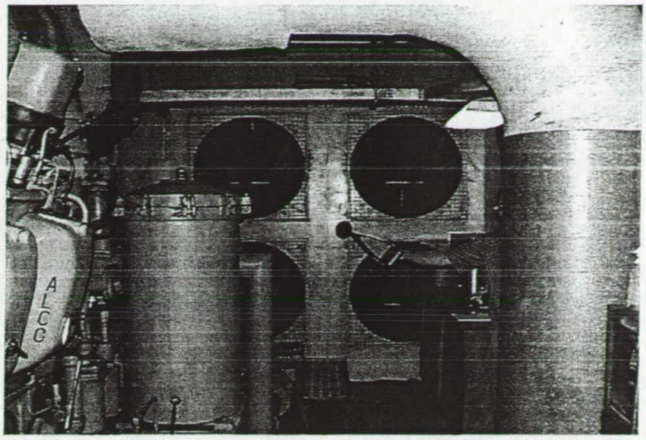

Figure 4. SPL Measurement in front of an Old Inlet Fan Set

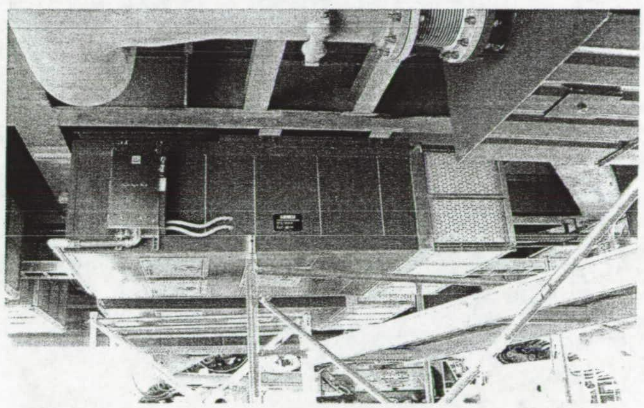

Figure 5. One of the 12 Acoustical Inlet Hoods under the CT with filtered air inlets

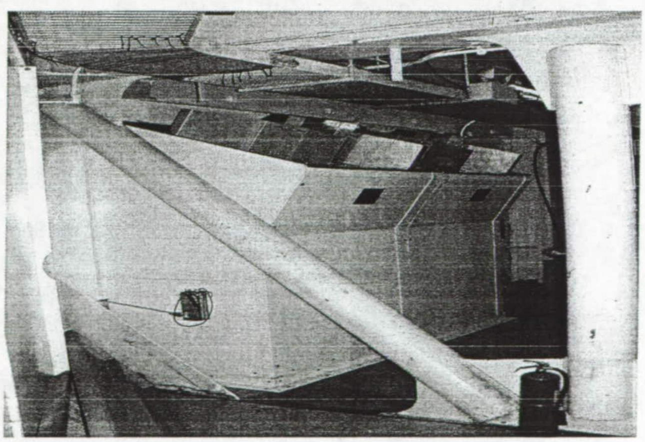

Figure 6. New double Exhaust Hoods installed in place of Old Inlet fans